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Foams and gels as fire protection agents

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Abstract

Fire protection foams and gels are used as temporary barriers to protect samples from incident thermal radiation thus delaying their ignition. Comparative measurements of the thermal behavior of these agents are made using a radiant heat exposure. The results of this comparison clearly show that thermal protection is obtained by two different mechanisms. The conduction-dominated gel operates at near saturation conditions (100°C). The radiation-dominated foam provides complete protection at ambient conditions (20–30°C) for about half the transient duration. Thereafter, the residual foam layer cannot prevent a rapid heat-up of the sample. Tests are performed applying the agents to a flat sample that is then positioned vertically and exposed to radiant heat. The lateral ignition and flame spread test (LIFT) apparatus is used to determine the ignition delay time for the gel. Due to the sample size restrictions associated with the LIFT apparatus, data collection for foams is not possible. Therefore, measurements are conducted in a Radiant Exposure Apparatus (REA) which allows for larger samples subjected to uniform heat fluxes up to 18 kW/m^2. The data gathered from the LIFT and REA are compared to establish the consistency between the two measurement sets.

1. Introduction

Madrzykowski [1] provides an early investigation of the behavior of foams used as fire protection agents. The flow characteristics of foam liquid solutions are described by Bobert [2] and by Gardiner [3]. Two recent studies model the behavior of these agents: Staggs [4] discusses the transient conduction processes governing the vaporization of a gel layer while Boyd [5] presents a first approximation model of the radiant processes involved in the destruction of a foam layer. These two papers provide the motivation for the experiments described hereafter.

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The emphasis of the present work is on the comparison of foams and gels intended as two classes of products rather than an investigation of the specific gel and foam products used here. In order to provide the necessary background, these foam and gel products will be described in the following section. A brief summary of the modeling efforts to date will also be provided to elucidate the mechanism underlying the thermal behavior of each agent when exposed to radiant heat. A qualitative set of considerations will follow to touch upon aspects that are beyond the laboratory experimentation described in the paper but that, nonetheless, are significant elements to be weighted in evaluating the performance of these agents in the field.

Following this background section, the description of the experimental apparatuses will be provided along with the test conditions. Finally, the experimental results will be presented leading to appropriate concluding remarks.

2. Background

2.1. Description of the gel characteristics and behavior

The gel is obtained by adding a gelling agent to water. The specific characteristics of the gelling agent used here are not described in detail due to the variability of this typical commercial product. The gelling agent can be added to water at various concentrations. The manufacturer recommended concentration of 1% is not suitable for repeatable controlled experiments in the laboratory. In the following, data will provide insight on the optimal gelling agent concentration to be used in the laboratory. Consequently, a concentration of 6% will be used for gel layers of 5 mm thickness. This thickness is an upper bound value for repeatable testing on vertical sample surfaces. Since the resulting gel is mostly water this yields a volume of 5 liters of water per square meter of surface protected.

The behavior of the gel is dominated by thermal diffusion. Staggs [4] adopts a transient conduction model and provides a reasonable description of the phenomena associated with the gel layer ablation. The radiant heat input is absorbed in the immediate proximity of the gel surface where saturation conditions are approached as the transient progresses.

2.2. Description of the foam characteristics and behavior

The foam used in the experiments is obtained from a protein-based concentrate that is added to water to form a 3% solution. The specific properties of this foam concentrate are not described in detail due to the variability of this particular commercial product. The foam is formed from the water-concentrate solution with compressed air.

To insure repeatable performance of the foam product, when applied to vertical surfaces in controlled laboratory conditions, the optimal range of expansion ratios (foam to initial liquid volume ratios) for the foam has been previously identified in the range between 13 and 26 [6]. A representative value of 20 is selected as the foam expansion ratio. The initial thickness of the foam layer is set to 0.1 m. This thickness provides a good balance of protection, ease of application and repeatability. Note that this foam layer yields a water volume of 5 liters per square meter of surface protected similarly to the gel layer previously described. Drainage is not significant for the protein-based foam used here due to the short time between the formation of the foam layer and its exposure to the radiant heat. Further, the radiant heat flux is sufficiently high to induce a foam evaporation rate that does not allow for significant drainage during the transient.

Data from a previous study [5] show that the foam thermal behavior is characterized by a period of time when the foam layer behavior can be considered quasi-steady state. This means that a Lagrangian observer, riding with the foam front, sees conditions that are constant in time. The foam front velocity is obtained from the energy balance on the whole foam layer. Typical values of 0.1 mm/s are obtained. This realization allows the formulation of a steady-state model that is used to gain insight on the contribution of the various heat and mass transfer mechanisms. The details of the changes occurring in the foam structure during the transient heat-up and vaporization are not investigated. Rather, the focus is on the overall foam layer thermal behavior. The most significant finding is that, when the foam is subjected to a radiant heat input of 18 kW/m^2, the peak of the radiant heat absorption is at about 30 mm below the surface of the foam. The radiant heat penetrates to depths up to 60 mm as shown in Fig. 1. The reason for this behavior is the decreasing density of the foam near

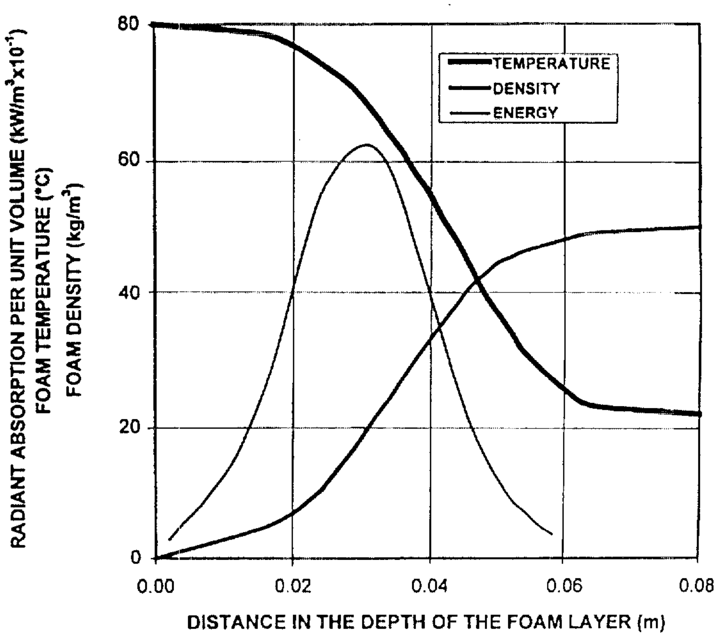

Fig. 1. Characterization of the foam layer measured from the layer exposed surface into its depth. The curves are obtained from a previously validated model [5] applied to a foam layer with expansion ratio of 20 exposed to a 18 kW/m^2 heat flux.

its exposed surface as the water is evaporated away from the foam matrix (see Fig. 1). As the density decreases, so does the absorption of the incoming radiation. In the depth of the foam layer, as the thickness and the density both increase, the radiant heat is absorbed causing the water to vaporize in situ since the contribution of thermal diffusion is small. The resulting temperature profile exhibits a plateau in the first 10–20 mm near the foam exposed surface (see Fig. 1).

2.3. Qualitative considerations

In the following, we will see how the differences between the two agents, previously described, will result in different thermal behaviors. These observations complemented with the following, more qualitative considerations, will provide insight for the selection of fire protection agents.

The first element to consider is the impact of wind. The lower density of the foam makes it more susceptible than gels to the possibility of being sheared away from the surfaces to be protected. This is an important issue if one considers that brush fires in wild-urban settings are usually accompanied by strong sustained winds.

A second element, relevant to the selection of the optimal agent, is the filling capability. The foam, with its high expansion ratio, is best suited to fill spaces that could otherwise be susceptible to accumulation of fire brands. For a house in a wild-urban fire setting, these brands could accumulate in eaves and corners generating a fire entry point into the structure. The gel cannot easily fill void spaces due to its much lower specific volume.

With this background information, we can proceed to examine the experimental evidence gathered in this study. To orderly proceed in the exposition of the arguments, we will first review the experimental apparatuses used in the investigation. The lateral ignition and flame spread test (LIFT) apparatus is used to determine the ignition delay time for bare wood samples and for samples coated with gel. The radiant exposure apparatus (REA), developed in the Building and Fire Laboratory of the National Institute of Standards and Technology [6], will be used to measure the ignition delay time for wood and aluminum samples coated with gel as well as for bare and foam-coated wood samples. The reason for this dual experimental apparatuses is to maintain sufficient one-dimensionality of the heat transfer processes for the tests with the foam. To comply with this one-dimensionality condition for the foam, a sample size, which exceeds the LIFT capabilities, must be used.

3. Experimental apparatuses

3.1. Lateral ignition and flame-spread test

The LIFT, consists of a radiant heat panel (280 mm high and 483 mm wide) capable of providing radiant heat fluxes up to 50 kW/m^2 at the center of the sample surface. The radiant heat panel is positioned vertically at a 15° angle with respect to the sample holder as shown in Fig. 2a. For the ignition delay time tests, the sample is

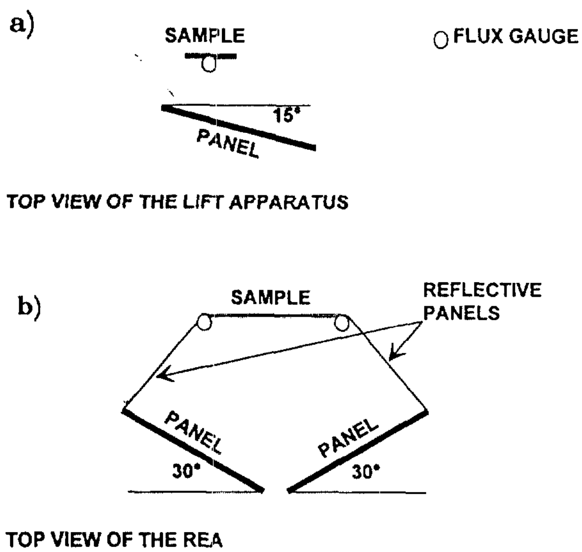

Fig. 2. Schematic representation of the experimental apparatuses.

square in shape (155 mm each side). An acetylene-air pilot is located at the top of the sample. The flux distribution along the width of the sample holder is known. The flux at the center of the sample is measured before each experiment. In the figure, the position of the flux gauge is identified. Note that, for the LIFT apparatus, the flux measurement is obtained when the sample is substituted with a plate holding the gauge. The back of the samples are covered with aluminum foil. The foil minimizes the premature ignition from the edges of the sample. The sample is placed in the sample holder exposing only the front surface and it is held in place by a marinite slab ensuring adiabatic conditions on the back surface of the sample. The ignition delay time is measured by using a stopwatch and the transient is recorded via video camera.

3.2. Radiant exposure apparatus

In the REA, two vertical gas fired panels, 0.38 m wide and 0.83 m high, are used to supply the radiant heat input. The flame is obtained from a regulated mixture of natural gas and air fed to the two panels. The panels are oriented at a 30° angle as shown in Fig. 2b. They are capable of generating maximum heat fluxes at the sample surface of up to 18 kW/m^2. This maximum heat flux is lower than typical fluxes present in a fire situation. However, it is sufficient to induce a foam vaporization rate that exhibits characteristics similar to those that would be observed at higher heat fluxes. This means that drainage and a more prevalent influence of thermal diffusivity are not significant at 18 kW/m^2. Both, drainage and thermal diffusivity, would be expected to become significant at sufficiently low heat fluxes.

Reflective panels are positioned as shown in the figure to minimize heat losses. The panel's orientation results in a nearly uniform radiant field at the sample surface (the variation at the sample surface is within 4% of the incoming heat flux). The sample is square in shape (0.3 m each side) and it is typically instrumented with thermocouples placed on its surface at various locations. Two flux gages are mounted on the sides of the sample to monitor the heat flux level during the test. The back of the samples is covered with aluminum foil and with a marinite slab similarly to LIFT set-up. A pilot is mounted at the top of the sample holder and it performs the same function of the pilot in the LIFT apparatus. The additional instrumentation installed in the REA enables a better description of the thermal behavior of the two agents.

The LIFT apparatus can accommodate square samples of 155 mm sides. The radiant panel is installed in close proximity to the sample (its minimum distance from the sample is about 0.15 m). Therefore, it is impossible to test the foam sample under these conditions since the initial foam layer used has a thickness of 0.1 m. In the REA, the sample surface is 3.75 times larger than in the LIFT. The foam sample exhibits reasonable one-dimensional behavior since the panels are positioned at a sufficient distance to provide uniform radiant heat flux, thus the sample edge and side effects appear to be negligible.

3.3. Test conditions and preliminary results

Commercial plywood samples are used both in the LIFT and REA while an aluminum plate is used in the REA to provide some indications of the effect of the substrate. The wood is kept at controlled temperature (23°C) and relative humidity (40%) prior to the test. Fig. 3 shows the ignition delay time of the bare wood samples in the lower portion of the plot. No ignition is observed at 10 kW/m^2. These data for bare wood are reported only to verify the quality and reproducibility of the results in comparison with similar tests performed with the REA. The maximum incident heat flux produced by the REA is 18 kW/m^2, therefore, the comparison of these two data sets is limited to the lower range of radiant heat fluxes. The figure shows excellent agreement for the ignition delay time for bare wood in the REA and LIFT. Note that each data point represents 3–5 repeat experiments.

The gelling agent is added to water at various concentrations. Two concentrations are tested here. A lower concentration of 3% yields reduced protection of the sample because the gel layer peels off during the test exposing the surface of the wood sample to the radiant heat. Therefore, a 6% concentration is used yielding satisfactory results for the duration of the test. Fig. 3 summarizes these observations. The gel results are reported only for the LIFT apparatus to show the difference in performance between the 3 and 6% gelling agent concentrations. The reason for this difference in performance can be found in the characteristics of the resulting gelling cake. At 3% concentration, the gel layer is still fluid. As the outer layer of the gel is exposed to the fire, water evaporates and the gelling agent concentration increases. This results in a fully caked layer in the proximity of the gel exposed surface. Between this layer and the sample surface the gel remains fluid. Therefore, the fully caked layer slides over the fluid sub-layer resulting in the exposure of the sample. At 6% concentration, the

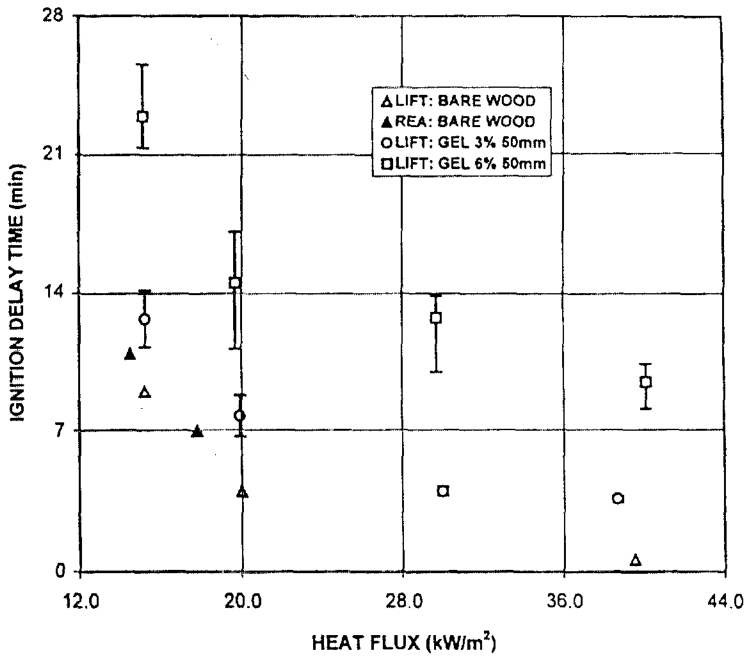

Fig. 3. Ignition delay time as a function of the radiant heat flux for bare wood and gel at various gelling agent concentrations.

whole gel layer is fully caked. Therefore, the gel layer is uniform in its texture. This results in a continuous protection of the wood until all the water is evaporated.

We can conclude that, for repeatable testing in the laboratory, the gelling agent application to vertical surfaces must yield a fully caked layer. This requirement may pose unrealistic constraints to the application methodology in the field since clogging of the supply apparatus must be avoided. Laboratory experiments with various gel layer thicknesses have been performed and 5 mm constitutes the upper limit of the layer thickness than can be applied to a vertical surface. For thicker layers a tendency of the gel to separate from the sample is observed with failures similar to those observed at 3% concentration of the gelling agent.

4. Results and discussion

In the following, we are considering experiments conducted with a radiant heat input of 18 kW in the REA. The gel concentration is 6%, as previously discussed, and the thickness of the applied layer is 5 mm. The foam is obtained from a 3% liquid solution with an expansion ratio of 20 which results in an initial foam density of 50 kg/m^3. The foam layer thickness is of 0.1 m. In both cases, the amount of water applied per unit surface area of the sample is 5 kg/m^2. Therefore, the comparison of the performance of the foam and gel is based on the same amount of water content.

4.1. Effect of the substrate

Fig. 4 illustrates the effect of the substrate when gel is used. Nine thermocouples in a square array are used to monitor the sample surface temperature. The standard deviation of the readings is indicated with the error bar and the curves represent the temporal evolution of the average of the readings. In addition to the wood samples, an aluminum sample is used. Its back surface is exposed to air to allow convective heat removal. In the early portion of the transient, the effect of the different sample materials (wood and aluminum) is not noticeable. The two traces are identical, considering the scatter of the temperature readings, up to about 9 min. The protection due to the gel layer extends for few more minutes. As the readings from the nine thermocouples becomes inconsistent and portion of the sample surface is found to be directly exposed to the radiant heat we identify this condition as the failure of the gel layer. The vertical lines at 9 and 14.5 min indicate the failure of the gel layer and represent the end of the protection time. During the protection time, the temperature of the samples remains below the saturation temperature of 100°C due to the ongoing

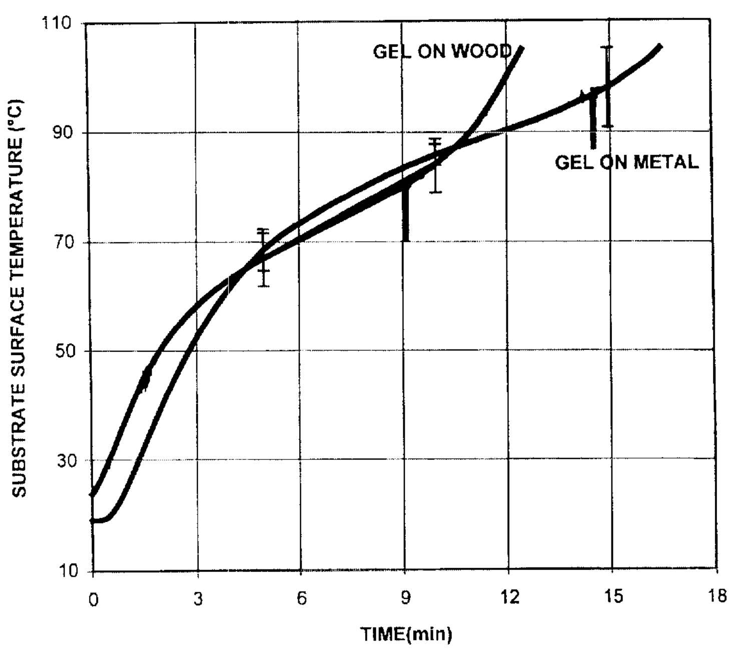

Fig. 4. Effect of the substrate: spatial averaged sample surface temperature as a function of exposure time. The gel is obtained for a 6% gelling agent concentration with an initial thickness of 5 mm. The heat flux is 18 kW/m^2 in the REA. The samples are commercial plywood and aluminum.

evaporative process. Toward the end of the transient, beyond 9 min, the wood sample exhibits a faster heat-up rate consistently with the inability of the substrate to efficiently transfer the heat away from the gel layer. The aluminum sample removes heat effectively and thus allows the gel to last about 5 min longer. In both cases, the sample surface temperature starts to increase as soon as the sample is exposed to the radiant heat input. This indicates that the heat wave propagates from the gel exposed surface to the sample very rapidly. In fact, for a semi-infinite layer of gel, suddenly exposed to radiant heat, the temperature, at a location 5 mm below the gel exposed surface, start increasing after 10 s.

4.2. Comparison of gel and foam

Fig. 5 illustrates the behavior of the foam in comparison with the gel. Both curves are for the average surface temperature of the wood sample placed in the REA with a radiant heat flux of 18 kW/m^2. The temperature at the sample surface exhibits a completely different behavior for these two agents. For several minutes, there is no indication that the sample coated with foam is exposed to radiant heat input. This is due to the strong insulating effect of the foam that exhibits very low thermal diffusion

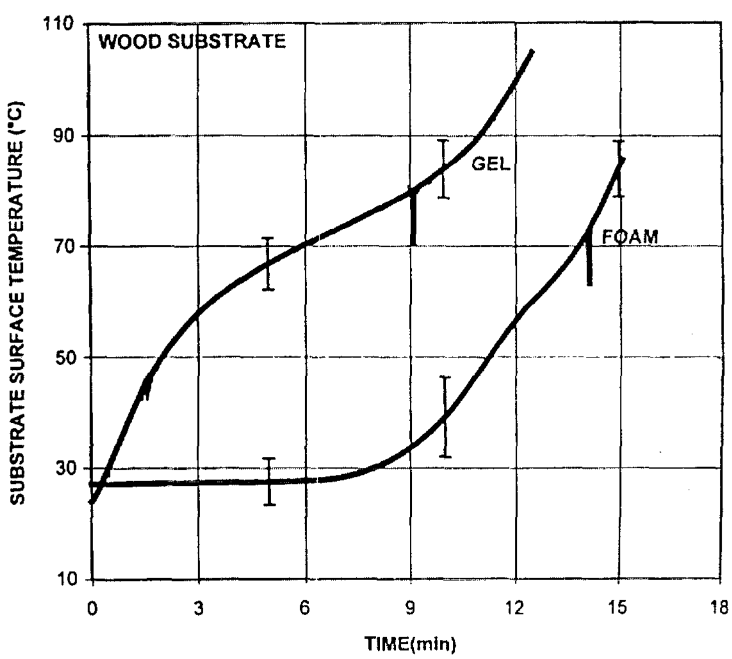

Fig. 5. Gel and foam comparison on a wood substrate: spatial averaged sample surface temperature as a function of exposure time. The gel is obtained for a 6% gelling agent concentration with an initial thickness of 5 mm. The foam layer has expansion ratio of 20 and an initial thickness of 0.1 m. Both tests are conducted with a heat flux of 18 kW/m^2 in the REA.

transport. Recall that the radiant energy is absorbed in the depth of the foam layer up to 60 mm into it. Recall also that the foam layer is receding at about 0.1 mm/s, it follows that the forefront of the radiant heat wave reaches the sample as 40 mm of foam are evaporated from the original 0.1 m layer. This would take place in about 7 min. This coarse estimate is consistent with the measurements shown in Fig. 5. Thereafter, the heat-up transient is steeper than for the sample coated with gel. The foam is completely evaporated in about 14 min. At this time, one finds inconsistencies in the temperature readings at the sample surface similarly to those for the gel tests described in the previous section. This indicates failure of the foam layer. The vertical lines at 9 and 14 min indicate the failure of the gel and foam layers, respectively. These times represent the end of the protective time. Note that the foam provides about 5 min of additional protective time.

Fig. 6 summarizes the results in terms of the ignition delay time. Gel data from the LIFT apparatus and the REA are shown to demonstrate the consistency of the measurement techniques. Note that the ignition of the sample coated with foam occurs about 5 min later than for the sample coated with gel confirming the previous observations on the protection time. The difference in thermal transport mechanisms (conductive for the gel and radiative for the foam) yields drastically different results for the temperature evolution of the sample surface. It is very important to note that for agents carefully applied in the laboratory, the ignition delay time with respect to the

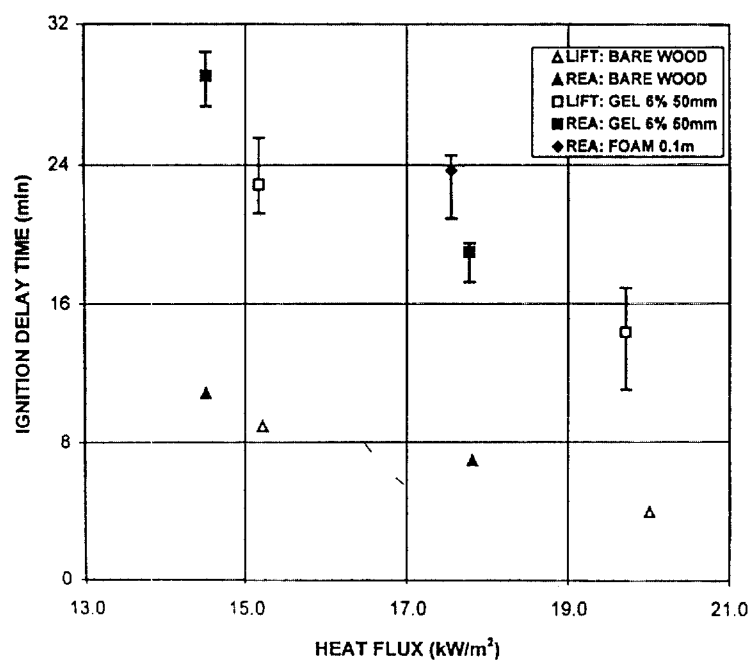

Fig. 6. Ignition delay time for bare wood, gel and foam for various conditions. The error bar bounds the maximum and minimum values and the data point represent the average of all tests performed.

ignition time delay for the bare wood can greatly increase. Each data point shown in the figure represents 3–5 repeat experiments.

5. Conclusions

Two fire protection agents have been tested to compare their thermal behavior when exposed to radiant heat. The two agents are a protein-based foam and a gel. Both agents have been tested to investigate the ignition delay time and the substrate temperature evolution when exposed to radiant heat input.

The effect of the substrate is negligible for a large portion of the transient which render these results applicable to most sample materials. The comparison of foam and gel shows that similar protection is provided by the two agents with significantly different mechanisms. The foam protects a surface at low temperatures for more than half of the overall transient duration. For application to vertical surfaces, the gel exhibits consistent performance for the duration of the transient provided that a sufficient agent–water concentration is used.

Some indications as to the optimal applications for these two agents are deduced from the comparison of the experimental results. This information, in addition to other considerations such as wind effect and filling capability could provide the base for an effective selection of the best suited agent for each specific fire situation.

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